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TITLE INTRINSIC NEUTRINO PROPERTIES: AS DEDUCED FROM COSMOLOGY, ASTROPHYSICS, ACCELERATOR AND NON-ACCELERATOR EXPERIMENTS

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INTRINSIC NEUTRINO PROPERTIES: AS DEDUCED FROM COSMOLOGY, ASTROPHYSICS, ACCELERATOR, AND NON-ACCELERATOR EXPERIMENTS

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ABSTRACT

I review the intrinsic properties of neutrinos as deduced from cosmological, astrophysical, and laboratory experiments. Bounds on magnetic moments and theoretical models which yield large moments but small masses are briefly discussed. The MSW solution to the solar neutrino problem is reviewed in light of the existing data from the ^{37}Cl and Kamiokande II experiments. The combined data disfavor the adiabatic solution and tend to support either the large angle solution or the nonadiabatic one. In the former case the ^{71}Ga signal will be suppressed by the same factor as for ^{37}Cl, and in the latter case the suppression factor could be as large as 10 or more.

1. Introduction

Were he alive today, Pauli would be amazed at the vast range of physics employed in the study of his 'last, desperate remedy' to solve the problem of energy conservation in beta decay. Cosmology, astrophysics, accelerator physics, and non-accelerator physics are all part of the search for neutrino physics beyond the standard electroweak model. The formation of primordial elements in the Universe itself[1] and the precise properties of the neutral Z gauge boson as measured at the LEP accelerator[2] both put limits upon the number of light neutrinos; both are converging on 3 at the present time. The spectrum of tritium beta-rays sets a bound on the mass of the electron-neutrino; and the generation and loss of energy in stars give rise to rare neutrino events in large tanks of liquids located deep underground which set limits on their electromagnetic and mixing properties. In my talk today, I would like to review all of these topics, but pay particular attention to bounds on magnetic moments and mixing properties. The emphasis is motivated by hints of a time dependence in the signal of solar neutrinos. Let me begin though with cosmology and its key connections with particle physics.

The central feature of Big Bang Cosmology is the Hubble expansion and consequent cooling of the Universe[3]. In the 'radiation era', when all particles are relativistic, there is a simple inverse relationship between time and temperature such that the larger the number of relativistic degrees of freedom, the faster the expansion and the less time needed to reach a given temperature. Since each species of neutrino

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makes its own independent contribution to the total number of degrees of freedom, it follows that the expansion rate of the Universe increases with the number of neutrino species.

Now, the number density of a given species of particle in a comoving volume will change with time in two respects: one is the Hubble expansion of the volume and the other arises from interactions with other species which can destroy and then recreate the particular species of interest, for example:

$$e^{+} + e^{-} \longleftrightarrow \nu_e + \bar{\nu}_e. \tag{1}$$

These two mechanisms tend to compete with one another, but at sufficiently high temperature the interaction mechanism will win out because the associated rates increase with temperature. In this regime, the interacting species will be in thermal equilibrium. As the Universe expands and cools, interaction rates decrease until the Hubble expansion becomes dominant and the species will 'freeze out', that is the total number will remain fixed,but the density will decrease in proportion to the Hubble parameter. Freeze out, or decoupling as it is often called, and its exact location in the temporal history of the Universe play an important role in nucleosynthesis and the primordial abundances of light elements. Hence the relationship between primordial ^4He and the number of light neutrinos[1,3].

Decoupling leaves behind whole species of particles which do not interact with each other through the strong and electroweak forces of particle physics, but which do exert gravitational forces upon the Universe. Whether one or more such species constitute the 'dark matter' is a question of varying opinions, but it does as we shall see, provide interesting limits on the masses and lifetimes of neutrinos, and even upon their magnetic moments.

Turning to astrophysics, we find that the neutrino provides us with signals of the nuclear reactions going on in supernovae and stars like our sun[4]. In the extremely dense concentrations of hadronic matter and electromagnetic plasma found in such bodies, the weakly interacting neutrino is the only known particle that can escape almost instantaneously. Some densities are so high, for example in the core of a supernova that even the neutrino gets trapped and has to diffuse out in somewhat the same way as do the much more strongly interacting photons. Neutrinos can be created in stars through such reactions as:

$$e^{-} + p \longrightarrow n + \nu_{eL}, \tag{2}$$

and

$$\text{'}Plasmon\text{'} \longrightarrow \nu_x + \nu_x, \tag{3}$$

and they provide one of the principal means of energy loss. As we shall see this can be used to set bounds upon neutrino properties.

In the case of the sun, the standard solar model (SSM) predicts a specific spectrum and flux of neutrinos produced in the fusion reactions which are the source of solar energy[5]. Parts of the spectrum, especially at the high energy end, are sensitive to the SSM and a failure to detect them in the predicted amount could be due to a breakdown of the SSM, or to mixing properties of the neutrino. Other parts of the spectrum, in particular the low energy pp neutrinos, have little sensitivity to the solar model and a failure to see them in the predicted quantities is a clear signal for neutrino mixing, oscillations, and mass.

Besides these cosmological and astrophysical methods of learning about neutrino properties, there are also direct laboratory methods. Some involve large accelerators, which have been used to probe neutral currents amongst other things[6]; reactors[7], which provide copious sources of low energy neutrinos; and other non-accelerator experiments such as the measurement of the tritium beta spectrum[8] and the search for double beta decay[9]. This large array of tools is used, of course, because the determination of neutrino properties, especially the demonstration that at least one kind of neutrino has a non-zero mass, will provide insight to physics beyond the standard particle physics model. The properties upon which I shall concentrate are: Majorana versus Dirac particles; masses; magnetic moments; and mixing.

2. Majorana Versus Dirac Neutrinos

From an operational point of view[10], the essential difference between a Majorana neutrino and a Dirac one lies in the ability to be reabsorbed by the same type of source from which the particle has been emitted. A Majorana neutrino emitted in the beta decay of one neutron can be reabsorbed by a second neutron and thus stimulate its transformation into a proton plus electron; a Dirac neutrino cannot. A more formal way of stating this is to say that Dirac neutrinos and anti-neutrinos have opposite 'lepton number' and behave in such a way that lepton number is conserved; Majorana neutrinos carry no lepton number and take part in processes in which it is not conserved.

In the context of the standard electroweak model of Glashow, Weinberg, and Salam[11], the distinction between Majorana and Dirac neutrinos is not meaningful unless the neutrino has a mass. The neutrino emitted by a neutron in beta decay is always right-handed, whereas the object absorbed by a neutron must be left- handed: in the limit of zero mass there is no overlap between these states of opposite helicity and the particles behave, for all practical purposes like Dirac neutrinos. When the neutrino has a mass, there can be an overlap between the two helicity states and hence the question of Majorana versus Dirac becomes a meaningful one. This dependence on mass holds up even in the case that there is a small admixture of right-handed currents in beta decay.

The most sensitive test for Majorana neutrinos is the search for no-neutrino double beta decay in which two neutrons inside a nucleus transform into two protons plus two electrons *without* the emission of two neutrinos:

$$2n \longrightarrow 2p + 2e_- . \tag{4}$$

The corresponding process *with* the emission of neutrinos,

$$2n \longrightarrow 2p + 2e_- + 2\bar{\nu}_e, \tag{5}$$

is allowed by the standard model independently of the question of mass and has been observed in the even-even isotope ^{82}Se with a lifetime of 10^{20} years[12].

Theoretically, the mass parameter to which the no-neutrino double beta decay amplitude is proportional[9] is a weighted sum over neutrino mass eigenvalues times mixing matrix elements U_{ei} times a CP-eigenvalue λ which may be even (+1) or odd (-1):

$$\langle m_{\beta\beta}\rangle_{LL} = \sum_i m_i \lambda_i U_{ei}^2 \tag{6}$$

Implicit in this expression is the assumption that the neutrino masses are much smaller than the momentum of the virtual neutrino exchanged between the two neutrons which typically lies in the range of 10-100 MeV. In the case when the effective weak interaction contains some admixture of right-handed currents, the effective mass has the form:

$$\langle m_{\beta\beta}\rangle_{LR} = \sum_i \left(\frac{U_{ei}V_{ei}}{(m_i)^2 + (p)^2}\right). \tag{7}$$

where V_{ei} is the mixing matrix for right-handed neutrinos.

At present the best limit on the half-life for no-neutrino double beta decay comes from the UCSB-LBL experiment[13] on ^{76}Ge. It is

$$T_{1/2} \geq 1.2 \times 10^{24} years \quad (90\% C.L.), \tag{8}$$

and it corresponds to a limit on the effective mass of

$$\begin{aligned} \langle m_{\beta\beta}\rangle_{LL} &\leq 0.6eV \;\; (Grotz, Klapdor) \\ &\leq 1.5eV \;\; (Haxton, Stephenson). \end{aligned} \tag{9}$$

The two limits in eq.(9) correspond to two different calculations of the nuclear matrix elements. Experiments are being planned in which highly enriched ^{76}Ge will be used in place of natural germanium and they are expected to push the limit on the half-life up by two orders of magnitude and the limit on the effective mass down by one order.

3. Direct Limits on Neutrino Masses

Direct limits on the masses of the electron-, muon-, and tau-neutrinos come from studying the end-point of the tritium beta spectrum[8], the decay of the charged pion at rest[14], and the decay of the tau-lepton into five pions respectively[15]. The best limit for ν_e comes from the Los Alamos experiment and it is $13.4eV$ (Since the talk was given, the Los Alamos group[16] has announced a new limit of $9.4eV$, and the Zurich group[16] has set a limit of $12.5eV$.)

The decay of the charged pion at rest into a muon plus ν_μ has been used at the Paul Scherrer Institute to set an upper limit on the ν_μ mass of $270keV$; and the Argus group at Petra has used the decay of the tau lepton into five pions plus a neutrino to set an upper bound on the ν_τ mass of $35MeV$. Both of these limits are much higher than the tritium bound for ν_e and the bounds obtained from cosmology.

Cowsik and McClelland[17] set the first cosmological limit on neutrino mass almost twenty years ago. Arguing that neutrinos would decouple from other matter (see eq. (1)) at a temperature of about $1MeV$, they used Big Bang Cosmology to estimate the number density of relic neutrinos in the present epoch. From measurements of the Hubble constant and the deceleration parameter, they could then put an upper bound on the density of all gravitational sources. Putting the two calculations together, they obtained a bound on the sum of neutrino masses:

$$\sum_{i=1}^{i=3} m_i \leq 40 - 100eV. \tag{10}$$

The range on the right-hand side reflects some uncertainty in the value of the Hubble parameter. As it stands this is quite a restrictive bound, and should we discover a new form of Dark Matter such as WIMPS, it could well become even more restrictive.

Lee and Weinberg[18] extended the above argument to set a *lower* bound on the mass of any heavy stable neutrino that might exist. They argued that a heavy neutrino would go out of chemical equilibrium at a temperature T_f much greater than $1MeV$ and that the mass on the left-hand side of eq. (11) must be replaced by the product of mass times a Boltzmann factor corresponding to T_f. This condition reproduces the above bound for small masses and it also yields a lower bound on large masses. The actual bound obtained by Lee and Weinberg was:

$$M_H \leq 2GeV \tag{11}$$

It has only just been superceded by LEP, which has placed a limit of about $45GeV$ on the mass of heavy neutrinos with full standard model coupling to the Z-boson.

Dicus, Kolb, and Teplitz[19] further extended the argument to unstable heavy neutrinos which decay to a light one plus a photon. They obtained a relationship between the mass of the heavy neutrino and its lifetime. For example a neutrino of $10MeV$ would have a lifetime of 2 years.

I now turn to the solar neutrino problem, where we shall encounter much smaller masses.

of 4. Brief Review of Solar Neutrinos and MSW The solar neutrino problem is now based upon two separate experiments, the original ^{37}Cl experiment of Davis and coworkers[20], and the Kamiokande II solar neutrino-electron scattering experiment[21]. Both report a deficiency in the number of neutrinos observed as compared with the predictions of the standard solar model[5] (SSM). In the case of ^{37}Cl the average capture rate over twenty years is

$$\begin{aligned} \langle capturerate \rangle &= 2.1 \pm 0.3 SNU \\ &= 0.45 atoms/day, \end{aligned} \tag{12}$$

while the standard model predicts a signal of

$$\begin{aligned} \langle SSM \rangle &= 7.9 \pm 1 SNU \\ &= 1.5 atoms/day. \end{aligned} \tag{13}$$

In the case of the Kamiokande II experiment, the ratio R of events observed to the number predicted by the SSM for the first 450 days of running is[21]:

$$R = 0.46 \pm 0.15 \tag{14}$$

(After this talk was given the experimental group reported a new result based upon an additional 590 days of running with a threshold of $7.5 MeV$ instead of the original $9.3 MeV$: the combined result of all the data is[22]

$$R = 0.46 \pm 0.05 \pm 0.06 \tag{15}$$

and shows no sign of a time dependence.)

Since both experiments are predominantly looking at the ^{8}B branch of the solar neutrino spectrum, and since this branch is very sensitive to the solar model, the deficiency could be explained either as a failure of the SSM, or as being due to new particle physics, namely neutrino oscillations. Crucial experiments in choosing between these two options will be the ^{71}Ga now being performed by two groups, SAGE and GALLEX, and the SNO experiment. The ^{71}Ga experiment will look at the pp branch which is relatively insensitive to the solar model, and a signal well below that of SSM will clearly support the new physics option. The SNO experiment will again measure the ^{8}B branch, but with much higher statistics than the earlier experiments, and it will look at both the spectrum of electron-neutrinos arriving at Earth and the neutral current reactions of solar neutrinos. Both signals will be key indicators for the choice between various explanations of the solar neutrino problem.

Being prejudiced towards oscillations and the matter enhancement of the MSW effect[5,23], I shall spend some time briefly describing these ideas. Neutrino oscillations is a purely quantum mechanical effect associated with coherent admixtures of two or more almost degenerate states and it can take place in vacuo or in a medium. When the phenomenon occurs in a medium its properties can be modified by the medium and this has become known as the MSW effect. For the case of oscillations between electron-neutrinos and muon- neutrinos, it is well-known that the former type can scatter from electrons via both weak charged- and neutral-boson exchange, whereas the latter can scatter only through neutral-boson exchange; thus the two types of neutrino have different refractive indices in matter and this will affect oscillations between them.

Consider two almost degenerate neutrino mass eigenstates ν_1 and ν_2, with masses m_1 and m_2 respectively, and with a common momentum p which is much greater than both masses. The two states have energies:

$$E_i = p + m_i^2/2p \quad (i = 1,2) \tag{16}$$

and as they evolve in time, they acquire the appropriate phase factors

$$exp(-iE_jt)(j = 1,2) \tag{17}$$

Hence the phase difference between them oscillates with time. Whenever new states are defined as coherent combinations of these two states with definite phase relations between them, the character of the new states will oscillate in time along with the phase difference.

The electron neutrino ν_e and the muon neutrino ν_m are defined as the orthogonal combinations:

$$\begin{aligned} \nu_e &= \cos\theta\nu_1 + \sin\theta\nu_2 \\ \nu_m &= \cos\theta\nu_2 - \sin\theta\nu_1. \end{aligned} \tag{18}$$

As these states evolve in time, the relative phase between ν_1 and ν_2 will change, and what was initially a pure ν_e or a pure ν_μ will become an admixture of the two flavor states.

Oscillations between the two flavor eigenstates can be described by a by a Schroedinger like time development equation which also enables us to take into account the MSW effect:

$$i\frac{dA}{dt} = HA \tag{19}$$

where A represents a column vector of the probability amplitudes for ν_e to remain ν_e and for ν_e to turn into another neutrino type ν_m, a_e and a_m respectively,

$$A = \begin{pmatrix} a_e \\ a_m \end{pmatrix}. \tag{20}$$

The Hamiltonian H is given by:

$$H = \begin{pmatrix} X & Y \\ Y & Z \end{pmatrix} \tag{21}$$

with

$$\begin{aligned} X &= \frac{m_1^2 c^2 + m_2^2 s^2}{2p} + 2^{1/2} G_F N_e \\ Z &= \frac{m_1^2 s^2 + m_2^2 c^2}{2p} \\ Y &= \frac{m_2^2 - m_1^2}{2p} cs = \frac{\Delta m^2}{2p} cs \\ c &= \cos\theta \\ s &= \sin\theta \end{aligned} \tag{22}$$

Matter oscillations are incorporated through the last term in the expression for X, which depends upon the Fermi constant G_F and the density of electrons, N_e. All the other terms in the expressions for X, Y, Z in eq (22) correspond to neutrinos propagating in vacuo. The matter term can have powerful consequences because it gives us a Hamiltonian matrix which is not only symmetric, but also one which can have equal elements down the diagonal. The eigenvectors of such a matrix are equal admixtures of ν_e and ν_μ, and so we have a chance to progress from non-maximal mixing in vacuo to maximal mixing in matter.

The condition for equal diagonal elements is:

$$2^{1/2} G_F N_e = \frac{\Delta m^2 \cos 2\theta}{2p} \tag{23}$$

Now the electron density N_e is inherently positive, and the Fermi constant G_F, since it arises from the exchange of a gauge boson, is also positive: therefore the product of Δm^2 and $\cos 2\theta$ must also be positive. It is not difficult to show that this requires ν_e to be dominantly composed of the lighter of the two mass eigenstates, and ν_μ of the heavier.

When we apply the MSW effect to the ^{37}Cl experiment of Ray Davis and his collaborators, we find that there are three types of solution in the parameter space of Δm^2 and $\sin^2 2\theta$: the *adiabatic* solution[24], in which 'low' energy solar neutrinos remain as electron-neutrinos while 'high' energy ones are almost completely converted to muon- or other neutrino types; the *nonadiabatic* solution[25], in which the 'low' energy neutrinos are completely converted to another neutrino type while the 'high' energy ones have about a 50% of remaining as electron-neutrinos; and the *large angle* solution[26], in which the probability for the solar neutrinos to remain as electron-neutrinos is independent of energy. The dividing line between 'low' and 'high' is in the neighborhood of 6-8 MeV.

The modified shape of the spectrum of electron-neutrinos from ^8B for both the adiabatic and nonadiabatic solutions is a key feature of the MSW effect and observation of either form of modification would establish neutrino oscillations in general and MSW in particular as the solution of the solar neutrino problem. Another important property of the nonadiabatic solution is that it can, for a certain range of parameters, yield a very small signal in the ^{71}Ga experiment because of the large conversion probability for low energy neutrinos; observation of such a suppression would also be a key signal for oscillations and MSW.

The Kamiokande II experiment observes solar neutrino scattering from electrons and, like the MSW effect, it too relies upon the charged-current diagram for its signal. Since the amplitude for the charged-current diagram is much larger than that of the neutral-current one, the cross-section for ν_e scattering turns out to be about 6 to 7 times larger than that for ν_μ scattering. Thus the observation in this experiment of a signal smaller than the prediction of the SSM can be interpreted as meaning that some or all of the ^8B neutrinos to which it is sensitive have been converted to muon-type neutrinos.

Figure (4d), from a recent paper of Bahcall and Haxton[27] shows how the MSW oscillation parameter space for the Kamoikande II result overlaps with the corresponding space for the ^{37}Cl experiment. It is evident that the adiabatic solution is disfavored at the present time, and that the non-adiabatic and large angle solutions are consistent with the two experiments.

While the large-angle solution predicts a fairly wide range of values for the ratio R in the solar neutrino electron scattering experiment, the non-adiabatic solution predicts that R should fall in a narrow range[28] around 0.5. It is interesting that the central value of the present result is very close to this value, suggesting that the non-adiabatic solution may indeed be the correct one. The ^{71}Ga experiment may well provide a test of this possibility because the central region of the non-adiabatic solution predicts an extremely small signal in gallium, whereas the large angle solution would tend to give the same suppression, a factor of 2 to 4, as in the chlorine experiment. Thus a very small signal in gallium would be a strong argument for the non-adiabatic solution first discussed by Rosen and Gelb[25]. (After this meeting. the SAGE collaboration presented its first preliminary results at Neutrino '90 which suggest that the gallium signal is very much smaller than the standard model prediction.)

4. Neutrino Magnetic Moments

The principal motivation for considering the possibility of neutrino magnetic moments at this time is the apparent anti-correlation between the signal in the ^{37}Cl experiment and the sunspot cycle: when the signal appears to be relatively high, around $4 SNU$, the sunspot number is low, and when the signal appears to be low, the sunspot number is high. Sunspots are a phenomenon associated with the appearence of kilogauss magnetic fields at the solar surface – the larger the number of sunspots, the more widespread the field. It is also thought that they signal the development of strong toroidal magnetic fields throughout the convection zone. Now, if the neutrino has a sufficiently large magnetic moment, somewhere between 10^{-11} and 10^{-10} Bohr magnetons[29], then its helicity can be flipped from left-handedness to right-handedness as it travels through the fields in the convection zone. Right-handed neutrinos cannot interact with ^{37}Cl and so the flipping of helicity leads to a reduced signal in the Davis detector. To the extent that the sunspot cycle reflects a cycle of increasing and decreasing magnetic fields inside the sun, the magnetic moment mechanism would lead to a corresponding cycle of decreasing and increasing signals in the ^{37}Cl experiment.

In general, the dipole coupling of neutrinos to the electromagnetic field strength tensor $F_{\alpha\beta}$ can be written as:

$$\mu_B \left(\bar{\psi}_a \sigma_{\alpha\beta}(x + y\gamma_5)\psi_b\right) \times F_{\alpha\beta}, \tag{24}$$

where the spinors ψ_a and ψ_b represent neutrinos of types a and b, and x is the magnetic dipole moment and y the electric dipole moment in units of the Bohr magneton μ_B. By virtue of the properties of the Dirac matrices, the interaction transforms a left-handed ν_{bL} into a right- handed ν_{aR}. When a and b represent the same type of neutrino, the dipole moments change sign under the interchange of particle and anti-particle. Thus Majorana neutrinos cannot have diagonal moments; they can, however, have transition moments from one type to another.

We can actually classify magnetic moments into three categories: diagonal, Dirac transition, and Majorana transition moments. Diagonal moments transform the left-handed neutrino of a given type into the right-handed neutrino of the same type, for example:

$$\nu_{eL} \longrightarrow \nu_{eR} + \gamma \tag{25}$$

and Dirac transition moments transform it into a right-handed neutrino of another type:

$$\nu_{eL} \longrightarrow \nu_{\tau R} + \gamma \tag{26}$$

Majorana transition moments always transform the left-handed neutrino of one type into a right-handed *anti-neutrino* of another type, transitions to the same type being forbidden by Fermi-Dirac statistics:

$$\nu_{eL} \longrightarrow \bar{\nu}_{\mu R} + \gamma \tag{27}$$

Notice that diagonal and Dirac transition moments conserve either separate or total lepton number, while Majorana moments change total lepton number by two units. In the standard electroweak model, however, the first two moments transform left-handed neutrinos into 'sterile' neutrinos which do not interact with matter; the Majorana moment, by contrast, transforms it into an 'active' anti-neutrino. This property will be important when we come to supernova neutrinos.

Limits on magnetic moments have been obtained from a wide variety of arguments and experiments. As we shall see the most stringent ones have come from astrophysics, and the tend to be at least one order of magnitude better than those obtained from experiment, and sometimes two. The important question from the point of view of this talk is whether they exclude moments of the magnitude needed to explain a possible time-dependence of the ^{37}Cl experiment.

In 1981, J. Morgan[30] noted that a diagonal moment for the electron-neutrino would allow a new interaction between electrons and neutrinos in the cosmological era, namely

$$\nu_{eL} + e \longrightarrow n_{eR} + e \tag{28}$$

For this reaction to decouple early enough so as not to interfere with nucleosynthesis, Morgan argued that the magnetic moment should be less than $1.5\times10^{-11}\mu_B$. Fukugita and Yazaki[31] subsequently re-examined the argument and softened the limit by a factor of 3 to $5\times10^{-11}\mu_B$.

Astrophysical limits on all types of moment have been obtained by studying the cooling of stars through the decay of a plasmon into a pair of neutrinos through couplings as in eqs. (25,26,27, and 1) above. While the density at the core of stars is much greater than that of the earth it is still possible for the neutrinos to escape almost instantaneously. To prevent a rapid collapse of the stars, the magnetic moments must not exceed some upper bound. The most recent bounds come from analysis of helium-burning stars: Raffelt and Dearborn[32] originally set a limit of $3\times10^{-11}\mu_B$ and Fukugita and Yazaki[31] pushed it down to $1.1\times10^{-11}\mu_B$. More recently Raffelt[33] has lowered the bound by an order of magnitude to $3\times10^{-12}\mu_B$ on the basis of mass considerations in globular cluster red giant stars. This limit is exceedingly dangerous for the solar neutrino question.

Laboratory limits on magnetic moments have been obtained from neutrino-electron scattering experiments with reactor neutrinos ($\bar{\nu}_e$) and with accelerator neutrinos (ν_μ). The upper bound from reactors[34] is $4\times10^{-10}\mu_B$ and from accelerator experiments[35] it is $8.5\times10^{-10}\mu_B$; neither one is as restrictive as the bounds discussed above.

An interesting and important bound on diagonal and Dirac transition moments can be obtained from the supernova SN1987A, and it is based upon the following idea first suggested by A. Dar[36]. Densities in the core of a supernova are so high that even neutrinos can be trapped inside them as long as they interact 'actively' with matter. Now if an active neutrino has a diagonal or Dirac transition moment, it can scatter from matter and be converted to a sterile neutrino. The sterile neutrino then has an excellent chance of escaping from the core without further interactions and with no further degradation of its energy; this means that it can carry away the $2-4\times 10^{53}$ ergs of energy released by the supernova explosion much more rapidly than active neutrinos.

Therefore the existence of diagonal and Dirac transition moments will have two consequences for the supernova: (i) the collapse will be much faster than in the standard case; and (ii) the emission of higher energy, but sterile neutrinos (with energies of order $200 MeV$ instead of $20 MeV$) which can, in their long passage (160,000 light years) through the weak intergalactic magnetic field, have their helicities reflipped from right-handed to left- handed. Our failure to observe either one of these effects can then be used to set bounds on the two lepton conserving moments.

The density in the collapsed core of the supernova is $8\times 10^{14} gms/cm^3$, about three times nuclear density, the temperature is in the range of $30-70 GeV$, and the radius is 10 kilometers. Mohapatra and Barbieri[37] estimate the luminosity of right-handed neutrinos to be:

$$Q(\nu_R)\approx(4-40)\times\left(\frac{\mu}{10^{-10}\mu_B}\right)^2\times 10^{55} ergs/sec. \tag{29}$$

Requiring $Q(\nu_R$ to be less than $10^{53} ergs/sec$, they obtain a bound on the magnetic moment of:

$$\mu\leq(2-8)\times 10^{-12}\mu_B. \tag{30}$$

From the absence of higher energy neutrinos in the IMB and Kamiokande II detectors, they obtain an even more restrictive limit:

$$\mu\leq(0.1-1)\times 10^{-12}\mu_B. \tag{31}$$

From the known cross-section for magnetic moment scattering of neutrinos by electrons, Latimer and Cooperstein[38] estimate the neutrino helicity flip rate to be:

$$R_{flip}\approx 4\times 10^{10}\left(\frac{\mu}{10^{-10}\mu_B}\right)^2 Y_e(1+B_f)\left(\frac{\rho}{\rho_0}\right) sec^{-1}, \tag{32}$$

where Y_e is the ratio of electrons to baryons in the core and is about 1/3, and B_f is the Pauli blocking factor for electrons and is roughly 1/2. The density ρ is approximately 3 times the nuclear density ρ_0. Assuming density ρ is approximately 3 times the nuclear density ρ_0. Assuming that 10^{57} neutrinos are emitted with an average energy of $200 MeV\approx 3.2\times 10^{-4} ergs$, they find a ν_R luminosity somewhat larger than that of Mohapatra and Barbieri, namely

$$Q(\nu_R)\approx 2\times 10^{58}\left(\frac{\mu}{10^{-10}\mu_B}\right)^2 ergs/sec, \tag{33}$$

and hence an even more severe limiton the magnetic moment:

$$\mu \le 2.2 \times 10^{-13} \mu_B. \tag{34}$$

Several other groups of authors have obtained similar limits within this range. The general conclusion is that the supernova rules out diagonal and Dirac transition moments of the magnitude needed to explain any time variation in the chlorine solar neutrino experiment. It does not, however, rule out a Majorana magnetic moment, which converts a left-handed neutrino into an active right- handed *anti-neutrino.* Thus the sun plus the supernova SN1987A suggest that the electron-neutrino may have a Majorana transition moment in the range of 10−11 to 10−10 Bohr magnetons.

5. Theoretical Models for Magnetic Moments

In the standard electroweak model, both the mass and the magnetic moment of the neutrino vanish identically because the model does not contain a right-handed *neutrino.* Thus models for the magnetic moment must involve extensions of the standard model. In the simplest extension, in which a right-handed neutrino is simply added to the spectrum of particles as a weak singlet, the magnetic moment is proportional to the mass[39]:

$$\mu(\nu_e) = \frac{3eG_F}{8\sqrt{2}\pi^2} m(\nu_e) = 3 \times 10^{-19} \frac{m_\nu}{1eV} \mu_B. \tag{35}$$

Given the limits on the neutrino mass, it is clear that the simple extension will never yield a magnetic moment large enough for the solar neutrino problem.

This example illustrates a general problem for model builders, namely to obtain a relatively large magnetic moment, in the ballpark of 10^{-11} to 10^{-10} Bohr magnetons, without giving rise to a large neutrino mass, or to large flavor changing processes like $\mu \to e = \gamma$, or to anomalous terms in the regular muon decay interaction. Most of the successful models extend the Higgs sector,adding additional charged Higgs bosons to the particle spectrum and invoking some additional symmetry principle.

We have argued in the previous section that the kind of magnetic moment needed is a transition moment between the left-handed electron-neutrino and the right-handed muon anti-neutrino. Such a transition does not conserve total lepton number, but it does conserve the *difference* between L_e and L_μ. Moreover, conservation of this combination of quantum numbers also forbids processes like $\mu \to e = \gamma$; in fact it is equivalent to the original Konopinski-Mahmoud scheme[40] which assigned opposite lepton numbers to the negatively charged muon and electron so as to forbid the photon decay mode. Voloshin[41] has recently observed that if this quantum number is incorporated into an SU(2) symmetry, then it has some very interesting consequences for neutrino masses and magnetic moments.

If we write down a Majorana mass term connecting ν_{eL} and $\nu_{\mu R}$, then it will be symmetric under interchange of the two fields; a transition magnetic moment term between them, on the other hand, is anti-symmetric. Therefore, if the two neutrino fields are treated as a doublet with respect to an SU(2) which has $L_e - L_\mu$ as its third component, then the mass term will behave as a triplet under this SU(2), while the magnetic moment term will be a singlet. Consequently, perfect symmetry under this Voloshin-spin will guarantee that the neutrino remains massless while the transition moment can be made as large as desired. The trouble, of course, is that the symmetry can never be made perfect, and so the real problem is to keep the symmetry-breaking effects under control.

The basic strategy which has been employed to implement this symmetry scheme is the introduction of new, weak isoscalar charged Higgs particles[42]; usually one is positvely charged and another negatively charged. The Voloshin-spin symmetry ensures that the loop contributions to the mass from these diagrams cancel each other. The magnetic moment comes from the same loop diagrams with a photon coming off the charged Higgs line; because the Higgs have opposite charges an additional minus sign is introduced between the diagrams. Therefore the diagrams that cancel each other in the mass now add together constructively, and can generate a large moment.

If the magnetic moment is the correct explanation of the solar neutrino problem and these types of model are correct, then we might be able to detect the new charged Higgs particles at LEP. In addition we should see time-dependent effects in ALL solar neutrino experiments.

6. Conclusion

At the present time, the *best* evidence for neutrino properties beyond the standard model comes from the Sun, but it is not conclusive at this time. More experiments which look more thoroughly at the spectrum of ν_e arriving at Earth and which detect the neutral current interactions of all solar neutrinos are needed. Better statistics are needed to settle the issue of time dependence. In all of these respects the SNO and BOREX experiments will be definitive. I would like to conclude by observing that, despite these caveats,a low signal in the ^{71}Ga experiment would most definitely be a signal for new physics. The standard solar model predicts a signal of 132 SNU of which 71 come from the pp neutrinos, 34 from the ^{Be} neutrinos, 14 from ^{8B}, and the remainder from minor branches of the solar spectrum[5]. The pp neutrinos are the least sensitive to solar models and so a signal well below 71 SNU would be a clear indication for new physics associated with the neutrino. An extremely low signal would be strongly suggestive of the non-adiabatic MSW solution.

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